CANADIAN CLIMATE CENTRE

REPORT NO. 89-4

CLIMATE CHANGE AND WINTER WHEAT YIELD IN ONTARIO

by

Isaac Savdie

ATMOSPHERIC ENVIRONMENT SERVICE

DOWNSVIEW, ONTARIO

1989

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A publication of the Canadian Climate Program

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ABSTRACT:

A physical deterministic, crop development model (CERES) is used to simulate winter wheat production in Ontario. The outputs of two general circulation models (GISS and GFDL) are used to simulate the effect of the doubling of carbon dioxide on the climate. The modified temperature and precipitation patterns are used as input to the crop yield model to study their effect on winter wheat production. Both general circulation models give consistent results for Ontario, however yields from the GFDL's simulation appear to be lower in certain areas because of the lower precipitations associated with that model. The effect of climate change on the spatial distribution of yield is interpreted in light of winter survival, maturity date, thermal and moisture stresses, and soil-climate interactions.

RESUME:

On utilise le modèle CERES pour simuler la croissance et le rendement du blé d'hiver en Ontario. On utilise aussi les données de sortie de deux modèles de la circulation générale (GISS et GFDL) pour simuler l'effet de l'augmentation du bioxyde de carbone atmosphérique sur le climat. Les températures et précipitations résultant de ces simulations sont utilisées comme données d'entrée au modèle CERES pour étudier les répercussions qu'elles entrainent sur la production du blé d'hiver en Ontario. Les résultats découlant des deux modèles de la circulation générale semblent concorder assez bien, cependant le décroissement du rendement du blé d'hiver associé à la simulation du GFDL semble plus être plus accentué dans certaines régions dû aux faibles précipitations prédites par ce modèle. On explique les conséquences du changement du climat sur la distribution spatiale du rendement en fonction de la survie de cette culture, les dates de maturité, les stress thermiques et hydrique ainsi que les interactions sol-climat.

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CLIMATE CHANGE AND WINTER WHEAT YIELD IN ONTARIO

1.INTRODUCTION

Winter wheat, sometimes referred to as fall wheat, because it is planted in autumn, has traditionally been a major crop in southern Ontario. In 1986, 92% of all wheat production in this province was derived from winter wheat. In recent years, it is becoming increasingly prevalent on the southern Prairies where climatic conditions are the restrictive factor in further expansion of this valuable crop. On a worldwide basis, 75% of wheat production is derived from winter wheat. Because of the importance of this crop, the present study has been undertaken to examine the possible effects of a doubling of atmospheric carbon dioxide on the climate and its effect in turn on winter wheat production in Ontario.

2. ECONOMIC IMPORTANCE OF WINTER WHEAT IN ONTARIO

Ontario produces about three quarter million tonnes of winter wheat annually. Approximately 250 thousand tonnes are marketed domestically as a cash crop and are used for milling or processing, 50 thousand tonnes are destined for feed and seed, and the remainder is exported. Soft winter wheat, which used in pastry, is the main variety grown in Ontario.

Winter wheat, has as a cash crop, yielded a higher gross return than other cereals, but tends to yield less than corn or soybean. The main region of winter wheat production in Ontario is delimited by the following five counties: Elgin, Essex, Kent, Lambton, and Middlesex. This region produces approximately 55% of the total Provincial production, and 92% of the crop is produced in the area west of Toronto. Background information on the economic importance of winter wheat in Ontario is well covered by Smid (1978). Besides its economic importance, winter wheat has several distinct advantages. Its yield usually exceeds that of spring wheat. Because of its earlier maturity, it suffers less from early summer droughts. It eases the pressure of spring work, it is usually cut several weeks earlier than spring wheat thereby helping spread the use of harvest labour and machinery. It provides good protection against wind and water erosion during the fall, and usually competes better with wild oats and other weeds than spring wheat does. Winter wheat is however vulnerable to winter kill, and to diseases and insects which if left uncontrolled could devastate the crop. A sparse seeding will not provide protection against wind damage and weed problems, and finally failure to use proper cultural and control practices could result in complete loss of the crop. While this crop possesses several distinct advantages, recommended cultural and control practices have to be adhered to in order to avoid serious threatening hazards to which this crop is vulnerable. To that end an annual field crop recommendation guide (1988) is issued by the Ontario Ministry of Agriculture and Food.

3. FACTORS AFFECTING THE GROWTH AND SURVIVAL OF WINTER WHEAT

Several factors affect the development and survival of winter wheat. An excellent review of these was presented by Savdie (1988). The factors affecting winter wheat growth are climatological (temperature, precipitation, sunshine, radiation, wind), edaphic (soil texture and depth, nutrient content, water holding capacity), hydrologic (runoff, percolation) and genetically related (root depth, sensitivity to vernalization, hardiness, sensitivity to photoperiod, tiller formation, grain formation and grain filling rates, etc.). Cultural practices, fertilization, weed, pest and disease control also play a very important role in winter wheat production.

Vernalization, which is a drop in temperature during a sustained period, must be satisfied, before floral induction occurs. If such a requirement is not met, the crop does not go beyond the vegetative stage. Optimum growth is confined to a specific range of temperatures. Mean monthly temperatures exceeding 18°C are associated with a decrease in the rate of growth, grain formation and grain filling. The photoperiod requirement varies with the stages of development, however it averages 12 hours of sunshine (Chang, 1968) in the later stages.

Planting date is quite important in that it will determine whether a strong enough crop has been established during the fall to survive the winter, or whether a poorly developed root system will become vulnerable to harsh winter conditions. An early planting date can also render the crop vulnerable to plant diseases such as the streak mosaic.

Seeding depth will also affect emergence, survival and ultimately yield. An experiment at Agriculture Canada Research Station in Lethbridge, Alberta (1976) documents the effects of three seeding depths on winter wheat.

A well drained soil is quite important, particularly during the thawing and freezing cycles during the fall and early winter. A poorly drained soil which will allow the formation of an ice sheet that will cover the crop for over two weeks will result in a complete kill of the underlying crop. Freezing and thawing cycles will also mechanically uproot the young crop.

Snow cover is a mixed blessing, for while it provides the badly needed protection the plant needs during the cold winter months, it promotes disease during a protracted snow season. Snow mold will develop when the temperature at the crown level is around freezing. Strong winds will desiccate exposed young plants during the winter.

Winter wheat will harden and become dormant when gradually exposed to cold temperatures. The degree of hardening depends on the duration and intensity of the cold temperatures. Dehardening on the other hand depends on the rate of warming and the hardened stage at which the crop is found. Winter kill will result when a mild spell inducing dehardening is followed by an outbreak of cold arctic air.

Strong winds and hail could cause considerable damage to the crop, particularly if they occur close to the maturity stage when grains are filled and the plant is top heavy.

While precipitation is essential for growth and development, long periods of high humidity accompanied by temperatures in the 15° to 22°C range can promote leaf diseases such as powdery mildew, leaf rust, septoria leaf spot, and tan spots all caused by fungi which become active when these conditions are met (Ontario Ministry of Agriculture and Food, 1983).

4. LITERATURE REVIEW

A study of the impact of the change in climate as a result of a doubling of atmospheric carbon dioxide concentration as simulated by the output of the GISS (Goddard Institute for Space Studies) general circulation model on agriculture in Saskatchewan was completed in 1987 by G.D.V. Williams. While the study was quite comprehensive, it focussed primarily on spring wheat.

An earlier study conducted in 1980 by the National Defence University, NOAA, USDA and other cooperating research institutions, addressed the question of winter wheat on the global level, however arbitrary criteria were used in defining three climatic scenarios in which temperatures ranged from -3°C to +3°C and precipitation from -30 to +30% above normal conditions. More importantly, the study was quite subjective in nature and the probability of a climatic scenario's occurrence was "an expertise-weighted average of subjective probabilities that were solicited from a panel of climatologists". Furthermore the 6 countries for which the impacts were studied did not include Canada.

A somewhat more objective study of climate change and winter wheat was conducted in 1985 by C. Rosenzweig. The study concentrates on the "effects of the predicted climate changes on the geographic location of wheat production"; and covers North America. Once again the study uses GISS output to simulate the effect of the doubling on the climate, and used the length of the growing season, seasonal growing degree days, minimum monthly temperatures and total annual precipitation to delimit the areal distribution of spring and winter wheat. The study examines the shift in these areas as a result of a doubling of carbon dioxide concentrations. The results of the study extend the area of soft winter wheat production in eastern Canada and north to 55°N, well into the precambrian shield. Unfortunately the model does not take into account snow cover, for which winter wheat survival in Canada is so crucial. It was also unable in the control run to reproduce the winter wheat areas in western Saskatchewan and eastern Alberta, it does however provide a first guess of the areal distribution on the continental scale of that crop under a modified climate.

A year later, in 1986, the Land Evaluation Group of the University of Guelph conducted, under an Atmospheric Environment Service contract, a study on the impact of climatic change on Ontario agri-food sector, and in 1987, completed a second study on the implications of climatic warning on agricultural production and trade. GISS output was used again to simulate the impact of the doubling of carbon dioxide on the climate. The study not only reviewed the impact of the climate change on major field and horticultural crops, but explored the potential for new opportunities (crops that could be grown in the modified climate) in the Province. Winter wheat, which constitutes a major winter crop in the Province, was studied for a single location only and a single water holding capacity in the Province, while for the other crops, the analysis was conducted for 6 major regions. The calculations were based on normal seasonal values. The attainable seasonal dry weight yield was obtained from a constraint-free dry matter yield reduced by factors which simulated the effect of moisture stress, soil workability, soil aeration, average management practices, and the conversion from dry matter to dry weight. While the approach appears comprehensive, many input parameters were subjectively determined. The more recent study estimates that the decreases in winter wheat yield across Ontario will range from 10% to 20% as a result of climate warming simulated by GISS. Normal seasonal values have been used in their computations. This approach introduces uncertainties in the results as normal values will not reflect the seasonal sensitivity of the yield to climatic change, but more importantly, seasonal values will miss the sensitivity of various phenological and development stages to the modified climate. The results are also too general to reflect the spatial distribution of the impact of the modified climate on this important crop.

5. SHORTCOMINGS OF STOCHASTIC METHODS IN PREDICTING THE IMPACTS OF CLIMATE CHANGE ON AGRICULTURE

In the absence of a deterministic approach, a statistical one, in which a dependent variable is usually regressed on several independent variables, has been used in simulating crop yield. Such an approach has been widely used in the past. Micevic developed a set of regression equations for predicting winter wheat yield in Yugoslavia, and Thompson (1969) had done the same for five Great Plains states: North Dakota, South Dakota, Nebraska, Kansas and Oklahoma. Several shortcomings are associated with such an approach. The predictors are not usually truly independent, the sample size may not be large enough to accommodate the number of independent variables required, the statistical significance of the results are questionable and finally the computed coefficients could be unstable and may change in magnitude and/or in sign. The WMO expert committee on the reliability of crop-climate models for assessing the impacts of climatic change and variability (1984) goes as far as stating that "it is rarely possible to identify the physical or physiological significance of the coefficients which arise in multiple regression analysis". An excellent illustration of the instability of such coefficients was done by Katz (1979) in which the ridge regression technique is used to unmask the dependence of the predictors on each other. The result of his sensitivity analysis reveals that the "discrepancies among the ordinary least square models are due, not to regional difference, but to the inherent variability of the estimated regression coefficients".

More importantly, the coefficients developed in the current climatic conditions would be totally unsuitable in predicting the impact of a climate change on the yield, since these coefficients are inherent to the range of current climatic extremes from which they have been derived and would not thus be realistic for predicting changes associated with different climatic conditions, particularly if in the modified climate, new extreme conditions, or a combination of unprecedented conditions (i.e. precipitation, temperature, sunshine, wind etc.) are encountered. Such coefficients incorporate and synthesize in their sign and magnitude the inherent climatic conditions of a given location. Precipitation for example was found to be negatively correlated with yield (Thompson, 1969). Such a relationship might be valid in the current climate for a location which may be receiving more precipitation than required for the growth of winter wheat. In a modified climate however, where precipitation might drop well below the required threshold for optimal growth, the use of negative coefficients for precipitation becomes an absurdity.

A deterministic, crop development model, which tracks the crop response on a daily basis to environmental changes will better reflect the impact of a change in climatic conditions, particularly if these changes will affect the development at various critical phenological stages, and ultimately crop maturity and yield. Monthly or seasonal averages may miss or distort the impact of a climatic change. It is for the above reasoning that a deterministic model has been selected for this study.

6. THE CERES MODEL

6.1 BACKGROUND

CERES which is a Greek word for cereals, stands for Crop Estimation through Resource and Environment Synthesis. This model was developed by J.T. Ritchie in 1984 for the United States Department of Agriculture in Temple Texas as a result of the wheat yield project and AGRISTARS program (Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing).

Several applications for the model have been identified by the modellers, which include among others large area yield forecasting, policy analysis and definition of research needs. The model has been widely used in different parts of the world. It has been tested (Ritchie, 1984) with data from about 25 different sites ranging from latitudes from 36°S in Australia to 50°N in England. The model explains about 85% of the variance, which reflects its sensitivity to the factors causing yield variations.

6.2 MODEL DESCRIPTION

The CERES model is a physical, deterministic crop growth model. It tracks plant growth and development on a daily basis. The model has been developed to reflect the phasic development of the crop. The six growing stages modelled are germination to emergence, emergence to terminal spikelet, terminal spikelet to end of leaf growth, end of leaf growth to ear growth, ear growth to beginning of grain filling, and finally grain filling to maturity. Appendix A summarizes the phases modelled and the pertinent plant part growing during each phase. Appendix A also summarizes the parameterization, the thresholds and the variables involved in reaching each phase. The criteria for germination, emergence, hardening, dehardening, vernalization, winter kill, leaf formation, photosynthesis, grain formation and grain filling are described in detail by J.T. Ritchie (1984).

The model uses a layered soil, in which up to 10 layers can be specified by the user. Genetic coefficient governing the sensitivity to vernalization, day length, grain production, and grain filling rate are also user specified.

Potential evapotranspiration is calculated using a modified Priestley and Taylor formulation.

Planting date, sowing depth and planting concentration are also required.

The meteorological data required to drive the model are the daily total solar radiation, daily maximum and minimum temperatures, and the daily total precipitation. An internal algorithm is used to convert precipitation into snow when the daily maximum temperature drops below 1°C. A conversion rate of 1 cm of snow per mm of precipitation is used. Snow is melted at a rate proportional to the daily maximum temperature and rainfall amount.

The model outputs the julian dates for 8 phenological stages, the biomass accumulated, the leaf area index, and a measure of the moisture stress at each phenological stage. It outputs also the yield and final number of grains per square meter.

The model does not include however a simulation of plant disease, cultivation practices, damage due to pest, hail, strong winds and killing due to ice sheet formation, and to the thawing and freezing cycles during the fall and winter.

7. OUTPUTS OF THE GENERAL CIRCULATION MODELS USED IN STUDY

The outputs of two general circulation models in which the concentrations of atmospheric carbon dioxide have been doubled, are used in this study. The GISS (Goddard Institute for Space Studies, New York, USA) model which was developed by Hansen et al. in 1984 and the GFDL (Geophysical Fluid Dynamics Laboratory, Princeton, USA) model developed by Manabe and Stouffer in 1980. A description of these GCM's and other general circulation models is given by Bolin et al. (1986). Appendix C summarizes the main differences between 12 GCM's. The first two versions of the GFDL model are idealized models in which the topograghy is uniform, and half the domain is ocean the other land. From the Appendix, the main differences between the third version of the GFDL model (used in this study) and GISS are in their mathematical formulation, the parameterization of the radiative processes, the modelling of oceans, sea-ice, albedo and

clouds. The GFDL is a 9 layer, 15 wave rhomboidal spectral model, in which the annual cycle is included but not the diurnal (i.e. the diurnal radiation is held constant). The GISS model is also a 9 layer, but a grid point model in which both the annual and diurnal cycles are included. Both models predict ice thickness formation over the oceans. Also the GISS output is for a doubling of atmospheric carbon dioxide concentrations, whereas GFDL's output is for a quadrupling of the concentrations. The main differences between the two models are summarized below:

a. Ocean modelling

The ocean sub-model in GISS is a two slab layer, however it is only a single thermodynamic fixed layer in the GFDL.

b. Sea-ice

In GFDL, for deep snow, the albedo is set to 0.6 equatorward of 55° and 0.8 poleward of 66°S, and is linearly interpolated in between. The albedo is reduced for snow less than 1 cm of liquid water. In GISS, for deep snow the albedo ranges from 0.5 to 0.85 depending on snow age, and is reduced for conditions where the snow water equivalent is less than 1 cm.

c. Albedo

In the case of sea ice, the albedo is set to be 0.5 equatorward of 55°, 0.7 poleward of 66.5°, and linearly interpolated in between in the case of GFDL; in the case of GISS, the sea ice albedo is the same as that for snow if it is snow covered, and is set to 0.45 for bare ice.

d. Clouds

Cloud is held fixed in GFDL, whereas layered clouds is a function of relative humidity and vertical development type is a function of vertical mass flux in GISS.

There is a considerable divergence in the overall temperature increases between the two models. The overall warming predicted by GFDL for a quadrupling of carbon dioxide concentration is 4.0°C, whereas GISS predicts 4.2°C for a doubling of the concentrations.

The grid point values obtained from GISS and GFDL have been interpolated for 17 locations in Ontario using the method outlined by Maarouf (1980).

The absence of the diurnal cycle simulation and of ocean horizontal transport in the GFDL model makes its results somewhat unsuitable for agricultural applications as is cautioned by Bolin et al. (1986). However the output of the GFDL simulation is used in this study for comparative purposes.

8. SOURCES OF DATA

Thirty years (1951-1980) of daily values of maximum and minimum temperatures and daily precipitation as well as hours of sunshine have been used as input to the CERES model. The meteorological data have been interpolated for the location of 17 counties (see Figure 1) selected to represent the spatial distribution of this crop in Ontario. A spatial interpolation technique developed by A. Maarouf (1980) was used to interpolate for missing values of the meteorological variables for each of the locations. The technique consists in constructing a first order polynomial surface to describe each meteorological field using existing observations. The polynomial surface is then used to solve for missing data at the points of interest. Twenty five climatological stations have been used to generate the required polynomial surfaces. This method thus allowed the construction of continuous time series necessary for this study.

Total solar radiation required by the model was approximated using the empirical relation developed by Glover and McCulloch (1958) correlating the station latitude (L), the radiation at the upper limit of the atmosphere (Qa), maximum possible hours of sunshine (N), and observed hours of sunshine (n) with the total solar radiation (Q). The form of the equation is as follows:

$$Q/Qa = 0.29 \cos (L) + 0.52\ n/N$$

The radiation at the top of the atmosphere and the maximum possible sunshine hours were based on algorithms developed by Agriculture Canada.

A simplified algorithm for soil data required for the CERES model was obtained from Dr. D.G. Godwin of the International Fertilizer Development Center, Muscle Shoals, Alabama. The algorithm produced typical soil profiles for general soil type classes.

Genetic coefficients for the most widely grown variety of winter wheat in Ontario during that 30 year period of the study were obtained from Dr. L.A. Hunt from the Department of Crop Science, University of Guelph.

Seeding dates were obtained from A. Bootsma of Agriculture Canada.

Observed winter wheat yield were abstracted from data published by the Statistical Services Unit, Economic and Policy Coordination Branch of the Ontario Ministry of Agriculture and Food.

9. ANALYSIS METHOD

The simulated 30 year average yield was compared to the observed one. Data for a simulated climate after the doubling of carbon dioxide were obtained from outputs from the GISS and GFDL general circulation models for the locations of the selected counties. The interpolation technique outlined in the previous section was used to interpolate from the GCM's grid point values to the locations of interest. The 1951-1980 temperature and precipitation data have been modified to reflect the changes in temperature and precipitation patterns. Only total precipitation was required, the model used a temperature algorithm to discriminate between rain and snow. The CERES model was run once again with the modified climate. Outputs of the modified climate were contrasted with those generated with the present climate.

10.0 RESULTS

10.1 ACTUAL VERSUS SIMULATED YIELDS

Figure 1 displays the 17 counties used in this study. The observed higher yield values in Figure 2 around Essex (42.8 b/a), southern tip of Lake Erie, and Huron county (42.0 b/a) are associated with the warmer temperatures, the longer growing season and the higher water holding capacities of the soils (clay and loam). The higher values at York county (39.4 b/a) are associated with the loamy soil in that area.

The higher elevations, thus the cooler temperatures, in the Grey county, and the sandy soil (thus lower water holding capacity) in the Haldimand-Norfolk county are associated with the minima in these counties.

The colder temperatures, and the poorer soil quality of eastern Ontario explain the relatively lower values of the yield in that region.

The lower values in Northern Ontario are a result of the longer cold winter responsible for winter kill, the poorer soils, and snow mold resulting from a protracted winter season.

The simulated yields in Figure 3 are much larger than those observed because the model does not account for disease, pest, or management practices. The model reflects however the effect of climate on yield. No attempt has been made in this study to include the effects of cultivation practices, pest and disease, because their control is essentially a function of technological advances which will be difficult if not impossible to predict, particularly when the onset of a climate change remains unknown. The direct effects of an atmospheric carbon dioxide enrichment has not been addressed because of the poorly understood processes involved, the lack of observational data, and the lack of experimental data to parameterize these processes. See Appendix B, for an overview of the processes involved in the impact of carbon dioxide enrichment on yield.

The control run reproduces generally well the loci of high and low yields. It captures the centres of high yields in southern Ontario, the lower yields in Grey and Haldimand-Norfolk counties, and the lower yields in eastern and northern Ontario.

10.2 PREDICTED YIELDS

The simulated harvest dates in Figure 4 range from Julian day 190 (July 8th) in Essex county to 217 (August 4) in the county of Sudbury. There is a gentle gradient from south to north reflecting the cooler temperatures as we move northward.

With the GISS simulation the harvest date field, Figures 5 and 6, retains its shape, however the date is one month earlier virtually everywhere in the province. The associated decrease in yield is however non uniform. This complex pattern reflects the intricate and synergistic interactions between soil type, temperature and precipitation regime associated with the GISS simulation when the atmospheric carbon dioxide concentrations are doubled. The stronger decreases in the northern region could be attributable to the lower precipitation given by GISS, which will not only introduce moisture stress during the growing season, but more importantly will erode the protective snow blanket during the winter and thus expose the crop to killing temperatures which will still be encountered in spite of the warming. The higher temperatures during the growing season will also result in more frequent dry episodes and will expose the crop to more frequent maximum temperatures inhibiting yield particularly during the grain formation and grain filling stages.

Perhaps the most predominant factor in the decrease in yield, is the earlier maturity dates resulting from the GISS simulation. The earlier maturity dates indicate that the crop reaches its various phenological stages more rapidly at the detriment of biomass production (hence less organs production at the vegetative, reproductive and maturing stages, and consequently less yield).

In the GFDL simulation, the harvest dates in Figures 8 and 9, range from 11 to 22 days earlier than those of the control run. These maturity dates which are in fact later than those predicted by GISS are a result of the less intense warming predicted by GFDL and a higher decrease in precipitations over Ontario.

Once again, as with GISS, there is a general decrease across the province (Figure 10). It ranges from -8.0 to -19%. The sharp drop in yield over Huron (-18%) and Wellington (-19%) counties are associated with a considerable drop in precipitation simulated by the GFDL model in these locations. It is interesting to note once again the drop in yield in northern and eastern Ontario, associated probably with a more precarious snow cover during the winter due to the drop in precipitation amounts during the winter, as well as moisture and temperature stress during the growing season.

It is also interesting to note the close correlation between the areas of earlier harvest dates and higher decreases in yield. As mentioned earlier, this is explained by the fact that while the crop is reaching its phenological stages at an accelerated rate, the rate of biomass production at each stage is lower. It is also worth noting, that the lower increases in temperatures associated with the GFDL simulation are reflected in harvest dates that are later than those associated with the GISS simulation.

11. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

Several assumptions and approximations have been made, in the course of this study. The general circulation models outputs, which are at the global scale have been interpolated to obtain estimates at the county level. The extent to which the sub-grid phenomena (or the higher frequency processes in the case of the spectral model) have not been accounted for in the GCM simulation, will affect the validity of this interpolation. Solar radiation has been derived using sunshine data, and temperature and precipitation have been interpolated for the sites of interest. Planting dates, planting concentration, and planting depth have been approximated using average conditions, also genetic coefficients of a typical crop has been considered throughout the study. The effects of management practices, such as seeding in zero till, in stubbles, or in fallow have been ignored. The results are therefore a general indication of the impact of the changes in temperature and precipitation regimes on the yield of winter wheat.

The most striking difference between the GFDL and the GISS simulation are the strong decreases predicted by the GFDL over the Huron and Wellington counties due to the lower precipitation associated with the GFDL simulation. The difference between the two models is more of degree than in nature. There is a general overall decrease in the yield predicted by both models with stronger decreases in yield in Southern and Western Ontario (the highest winter wheat producing areas in the present climatic conditions) predicted by the GFDL simulation. Less consideration should be given to the GFDL results because of the deficiencies of that model as mentioned earlier.

The ability of technological advances to produce cultivars which will be more temperature, moisture stress, and disease tolerant, and the ability of these advances to produce more effective pesticides, herbicides and fungicides that will be able to combat the new conditions that will result from new settings of species competitions in the modified climate, and a better understanding of the direct impact of atmospheric carbon dioxide enrichment, will largely determine the final impact of the doubling of this element on the yield of this crop.

Future research could explore the impact of different cultivars, planting dates, irrigation strategies, and the inclusion of fertilization, and the impact of disease on yield. Alternatively, genetic characteristics of cultivars which will produce the highest yield under the modified climate, could be determined to allow breeder to aim for such characteristics.

In the longer run, a better understanding leading to a realistic parameterisation of the direct effects of atmospheric carbon dioxide could be included. Hopefully at such a time more realistic general circulation models would have been developed.

12. ACKNOWLEDGEMENT

The author would like to thank Dr. D. Stewart from Agriculture Canada for providing AES with the source code of the CERES model, Mr. A. Bootsma also from Agriculture Canada for supplying winter wheat planting dates, Dr. J.T. Ritchie for his invaluable comments, Dr. Hunt, for supplying the appropriate genetic coefficients, and Dr. Godwin for supplying a simplified version of the soil moisture parameters. The author would also like to thank Dr. Rosenzweig for several fruitful conversations.

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APPENDIX A

THE CERES MODEL

STAGE	EVENT	PARTS GROWING
A.	SOWING TO GERMINATION |<-- 1 DAY -->| DELAYED IF SOIL MOISTURE < THRESHOLD OR IF SOIL TEMP. < 3°C	
B.	GERMINATION TO EMERGENCE - COLD HARDENING: FUNCTION OF CROWN TEMPERATURE AND SNOW DEPTH. - HARDENING OCCURS WHEN CROWN TEMP. IS BETWEEN -1 AND 8°C FOR 10 DAYS AND WHEN IT IS <0°C FOR 12 DAYS. - TILLER KILLED AS A FUNCTION OF HARDENING INDEX. - DEHARDENING OCCURS WHEN CROWN TEMP > 8°C	ROOTS, COLEOPTILE
1.	EMERGENCE TO TERMINAL SPIKELET - THERMAL TIME REACHES 400 UNITS - VERNALIZATION DAYS AND PHOTOPERIOD MODIFY THE THERMAL TIME	ROOTS, LEAVES
	- LINEAR FUNCTION OF INTERCEPTED PHOTOSYNTHETICALLY ACTIVE RADIATION (P.A.R.) - P.A.R. = 50% OF INCOMING RADIATION - % OF INCOMING P.A.R. INTERCEPTED IS AN EXPONENTIAL FUNCTION OF THE LEAF AREA INDEX. - 3.05 GRAMS OF BIOMASS ARE PRODUCED FOR EACH MEGAJOULE OF INTERCEPTED P.A.R.	

STAGE	EVENT	PARTS GROWING
2.	TERMINAL SPIKELET TO END OF LEAF GROWTH - TILLER LOSS WHEN STEMS ARE ACTIVELY GROWING. - A TIME LAG FACTOR IS USED TO PREVENT EXCESSIVE LOSSES DUE TO LARGE DAY TO DAY VARIATIONS IN PHOTOSYNTHESIS RATES.	ROOTS, STEMS, EAR
	- DETERMINED BY BIOMASS PARTITIONED TO ROOTS - ROOTING PREFERENCE FACTORS DETERMINE DISTRIBUTION OF ROOTS IN SOIL	
	- GROWTH OF STEMS BASED ON GENETIC SPECIFIC CHARACTERISTICS	
3.	END OF LEAF GROWTH TO END OF EAR GROWTH	ROOTS, STEMS, EAR
4.	END OF EAR GROWTH TO BEGINNING OF GRAIN FILLING - GRAINS/PLANT IS A LINEAR FUNCTION OF STEMS, EAR WEIGHT AND GENETIC FACTORS. - SEVERE STRESS WILL REDUCE NUMBER OF GRAINS.	ROOTS, STEMS
5.	GRAIN FILLING - THERMAL TIME IS A FUNCTION OF GENOTYPE. - MAXIMUM GROWTH IS A FUNCTION OF GENETIC PARAMETERS. - KERNEL GROWTH RATE DECEASES AS TEMP. DROPS BELOW 17°C OR WHEN DEMAND OF ASSIMILATE EXCEEDS SUPPLY AVAILABLE	
6.	END OF GRAIN FILLING TO HARVEST	

APPENDIX B

DIRECT EFFECTS OF CARBON DIOXIDE ENRICHMENT ON CROPS

The direct effects of carbon dioxide enrichment on crop growth are still controversial and could not be adequately parameterized with the current state of knowledge and empirical data available. It has been shown that an increase in carbon dioxide concentration in the atmosphere will cause a short-term increase in photosynthesis. When the crop comes to a new steady state in equilibrium with CO2 concentration, the increase in photosynthesis is usually lower than that observed over the short term. The actual level of photosynthesis will depend on plant species and varieties, other environmental conditions and management techniques. Too few empirical data exist to allow adequate prediction of photosynthesis rates to be expected.

As CO2 increases, stomatal conductance, which is function of light, leaf water potential, temperature and atmospheric humidity, decreases. Some species have been shown to be more sensitive than others in stomatal conductance to increased CO2. The fundamental mechanisms of stomatal response to CO2 concentration are still unknown. Measurements show that water use efficiency of leaves is increased because of reduced conductance, however the net effect of increased CO2 concentration on actual water use is less well understood because of the increase in leaf area and root extension observed in high CO2 plants, which tend to increase overall water use and may counteract the effect of low transpiration per unit leaf area.

From the sparse data available, CO2 appears to either accelerate or delay flowering and senescence. These interactions may profoundly affect seasonal duration of growth.

Also a full response to CO2 concentration can occur only where light is not limited.

Temperatures also play a role in photosynthesis. At low temperature, the rate of organ growth is limited and can cause starch accumulation and feedback inhibition of photosynthesis. At high temperature, enzime degradation limits both photosynthesis and growth. Photosynthesis and growth are limited by temperature proportionally more at high CO2 than at current levels.

The growth response to CO2 is limited by insufficient nutrient availability, probably through complex mechanisms poorly understood. Also unknown are effects of CO2 concentration on nutrient uptake capacity and changes in root to shoot ratio in conditions of low nutrient supply.

Salinity stress, like water stress, increases the relative growth to CO2 by at least tow mechanisms: a) high carbohydrate generation for exclusion of salts from roots b) lower leaf conductance, thus a lower water consumption, and therefore a lower activity of salt exclusion. The impact of this interaction on different species competing in saline soil is unknown.

Differential species responses in flowering and seed production with increased CO2 will change reproductive potential and will affect competition among crop, weed and native species.

An excellent review of the state of art knowledge on the direct effect of increased CO2 concentration on vegetation was conducted by the U.S. Department of Energy (1985).

APPENDIX C

MODEL	GEO-GRAPHY	TOPO-GRAPHY	ANNUAL/ DIURNAL CYCLE	CO2 SIMU-LATION	TEMPE-RATURE INCREASE (K)	RESOLU-TION	OCEAN/ SEA-ICE
1. GFDL MANABE,WETHERALD (1975)	I	NONE	NO/NO	2xCO2	2.9	9 LAYERS	SWAMP(NO HEAT CAPACITY OR TRANSPORT) ICE COVER PREDICTED
2. GFDL MANABE,WETHERALD (1980)	I	NONE	NO/NO	2xCO2	3.0	9 LAYERS 5.0x4.5°	SAME AS 1
3. GFDL MANABE,STOUFFER (1980) __,WETHERALD (1981)	R	R	YES/NO	4xCO2	4.0	9 LAYERS 15 WAVES	66 M MIXED LAYER (NO HORIZONTAL HEAT TRANSPORT)/ICE THICKNESS PREDICTED
4. OSU GATES,COOK SCHLESINGER (1981)	R	R	YES/YES	2xCO2	0.2	2 LAYERS 4.0x5.0°	CLIMATOLOGICAL OCEAN, SEA SURFACE TEMPERATURE PRESCRIBED, ICE COVER PRESCRIBED.
				4xCO2	0.4		
5. OSU SCHLESINGER (1983)	R	R	NO/NO	2XCO2	2.0	SAME AS (4)	SWAMP(NO HEAT CAPACITY OR TRANSPORT) ICE COVER PREDICTED
6. NCAR WASHINGTON MESHL (1983)	R	R	NO/NO	2XCO2	1.3a 1.4b	9 LAYERS SPECTRAL (4.5X7.5°)	SAME AS (5)
7. NCAR WASHINGTON (1984)	R	R	YES/NO	2XCO2	3.5	SAME AS (5)	50 M MIXED LAYER (NO OCEAN HEAT TRANSPORT) ICE COVER PREDICTED
8. UKMO MITCHELL (1983)	R	R	YES/YES	2XCO2	0.2	5 LAYERS SPECTRAL	CLIMATOLOGICAL OCEAN, SEA SURFACE TEMPERATURE PRESCRIBED + 2 K
				2xCO2	2.2		ICE COVER PRESCRIBED
9. UKMO MITCHELL LUPTON (1984)	R	R	YES/YES	4xCO2	4.5	SAME AS (8)	SEA SURFACE TEMPERATURE PRESCRIBED + LAT. VARYING INCREMENT, ICE COVER PRESCRIBED
10. GISS HANSEN ET AL. (1984)	R	R	YES/YES	2XCO2	4.2	9 LAYERS	60-70 M MIXED LAYER WITH PRESCRIBED SEASONAL DEPTH AND PRESCRIBED HORIZONTAL TRANSPORT, ICE THICKNESS PREDICTED
11. OSU GATES, POTTER (1985)	R	R	YES/YES	2XCO2	1.5	SAME AS (4)	VARIABLE DEPTH MIXED LAYER
12. OSU GATES ET AL (1984) SCHLESINGER ET AL. (1985)	R	R	YES/YES	2XCO2	1.5	SAME AS (4)	COMPLETE OCEAN GCM

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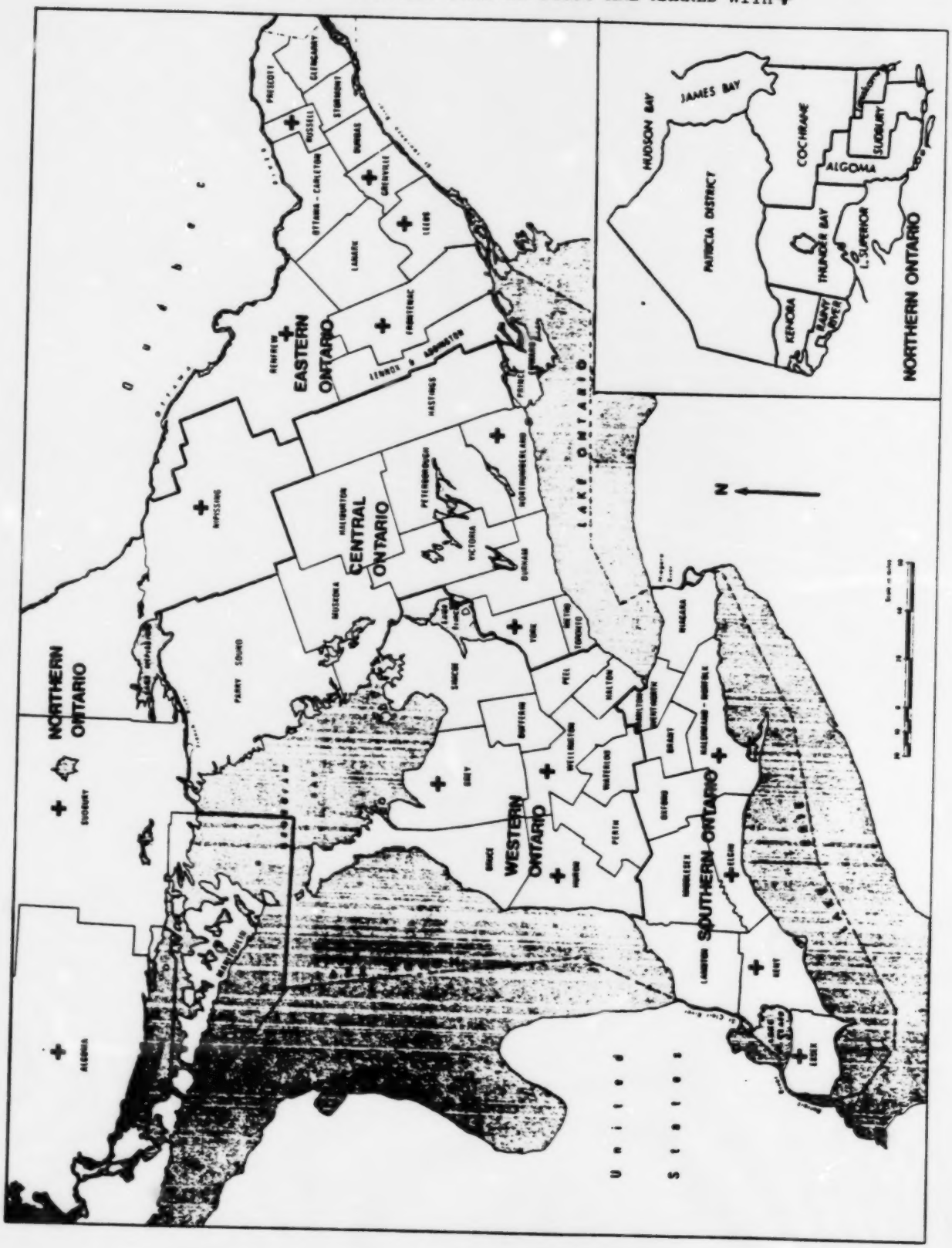
a: CLOUDS PRESCRIBED
b: CLOUDS PREDICTED
I: IDEALIZED
R: REALISTIC
GFDL: GEOPHYSICAL FLUID DYNAMICS LABORATORY, PRINCETON, USA.
GISS: GODDARD INSTITUTE FOR SPACE STUDIES, NEW YORK, USA.
NCAR: NATIONAL CENTER FOR ATMOSPHERIC RESEARCH, BOULDER, COLORADO, USA.
OSU: OREGON STATE UNIVERSITY, CORVALLIS, USA.
UKMO: METEOROLOGICAL OFFICE, BRACKNELL, UK.

FIGURE 1 COUNTIES USED IN STUDY ARE MARKED WITH +



OBSERVED AVERAGE YIELD OF WINTER WHEAT (B/A)

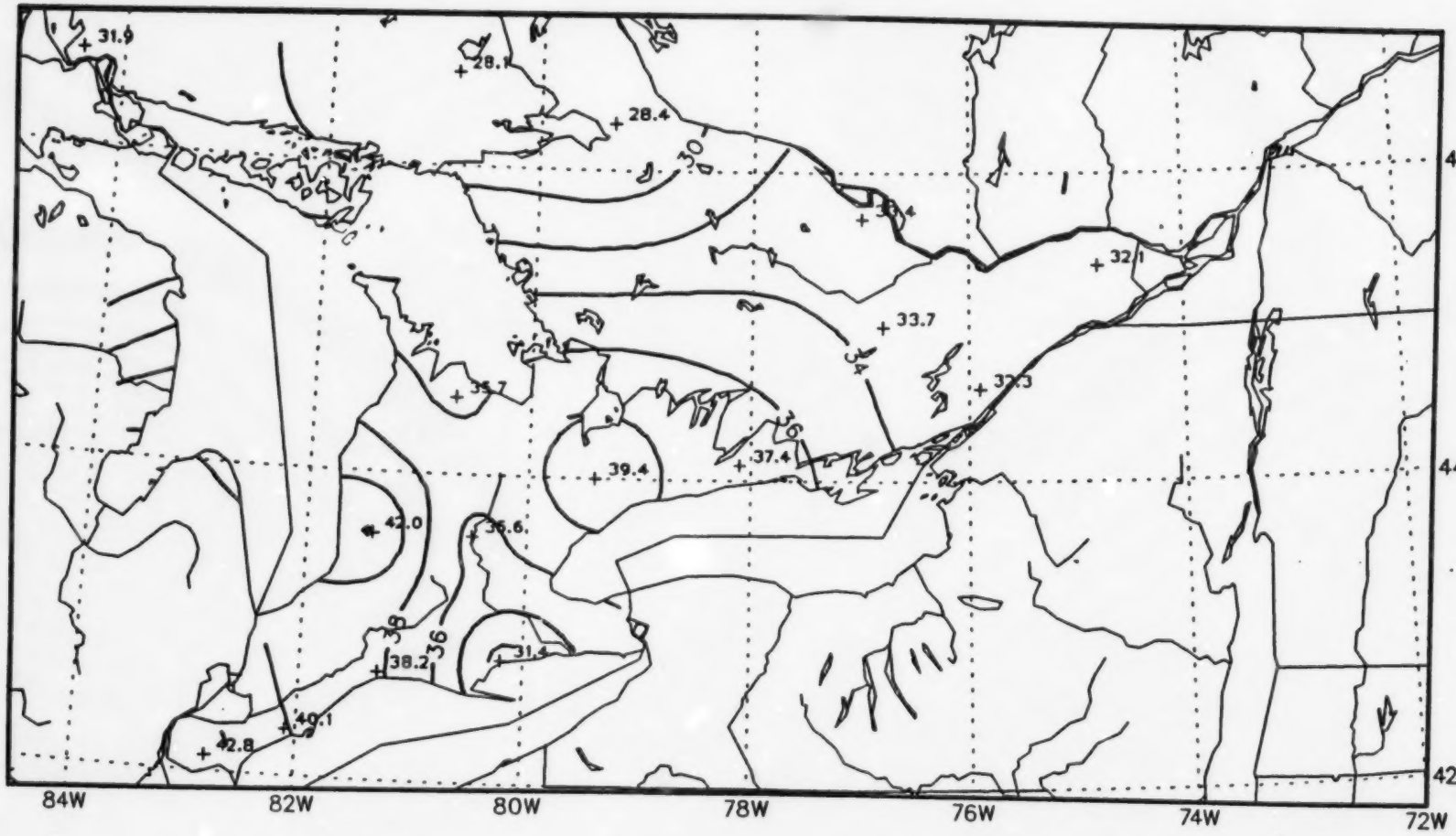


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FIGURE 2

SIMULATED AVERAGE YIELD OF WINTER WHEAT (B/A) USING CERES MODEL

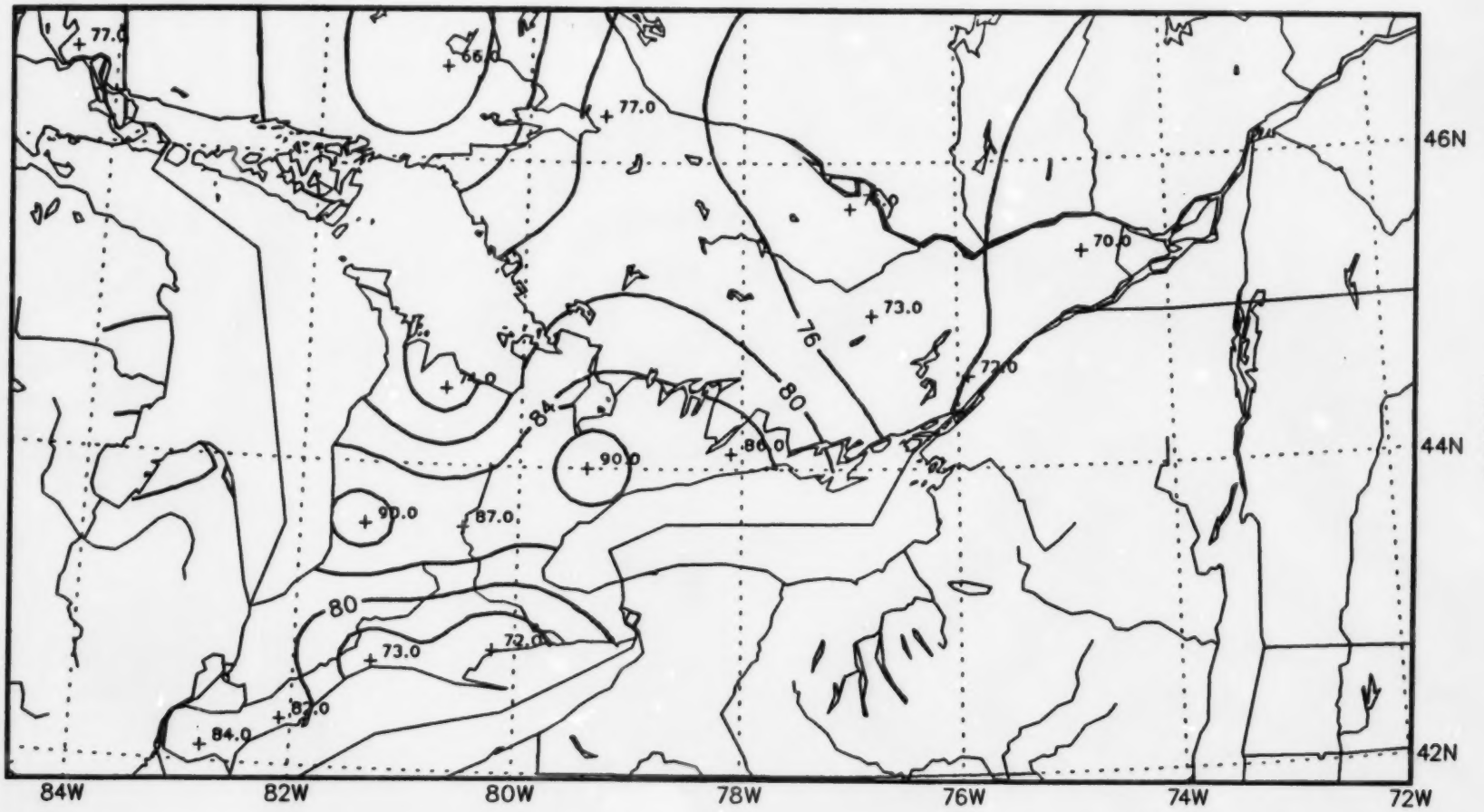

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FIGURE 3

HARVEST DATES SIMULATED BY CERES

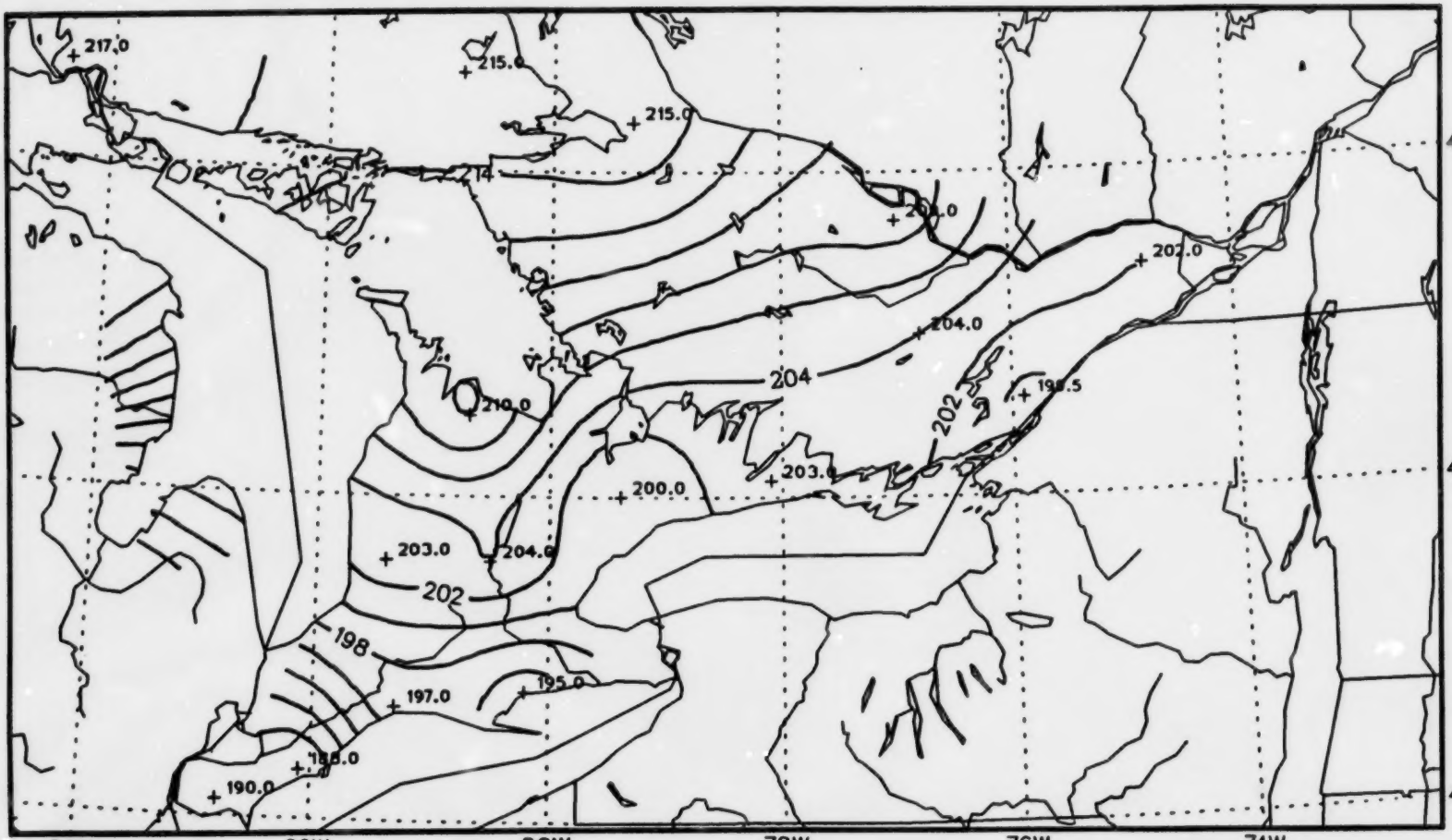

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FIGURE 4

AVERAGE HARVEST DATE FROM GISS SIMULATION

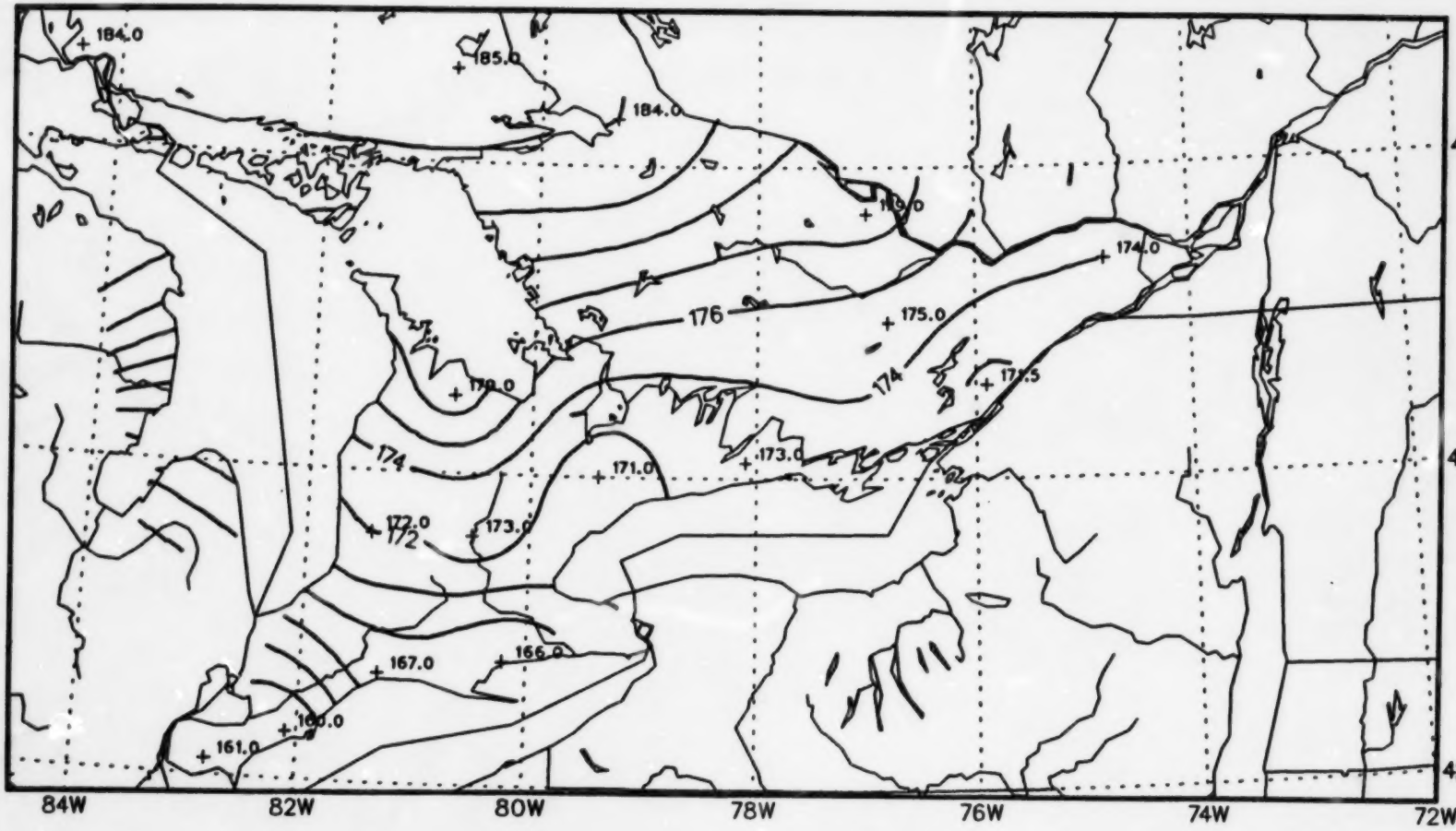

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FIGURE 5

CHANGE (IN DAYS) IN HARVEST DATE FROM GISS SIMULATION

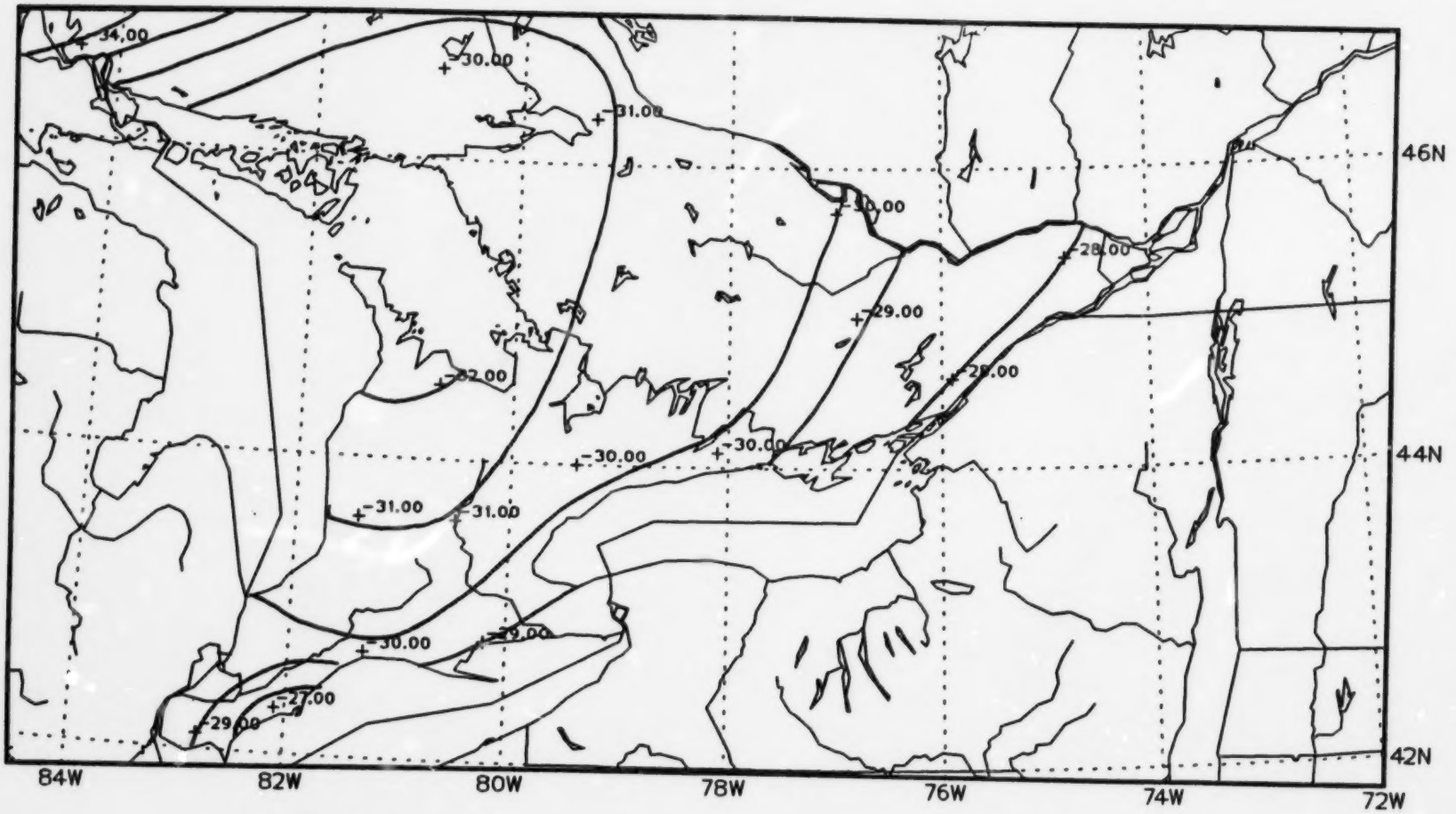

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FIGURE 6

CHANGE IN YIELD (%) AFTER CO2 DOUBLING USING GISS

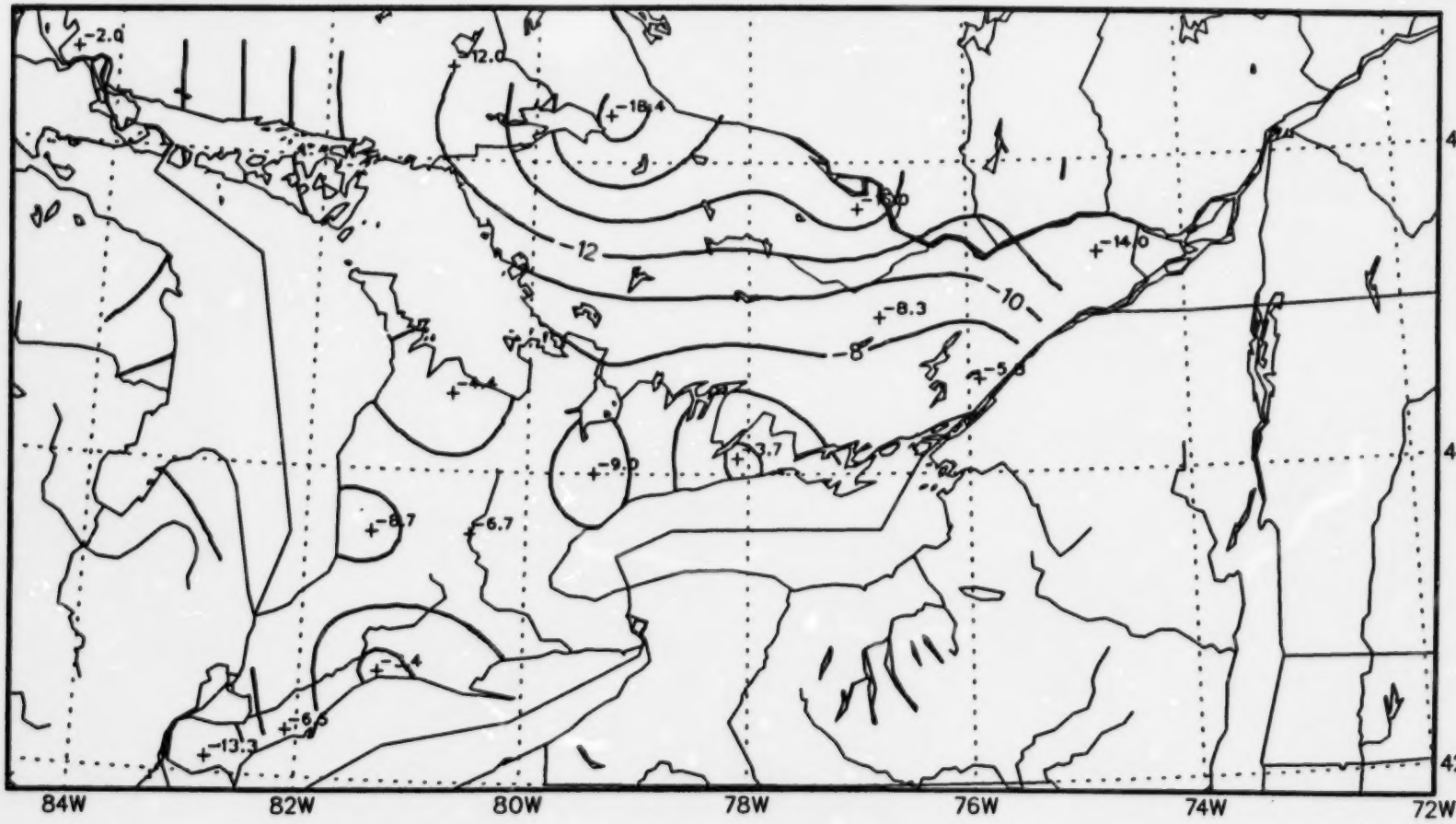

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FIGURE 7

AVERAGE HARVEST DATE FROM GFDL SIMULATION

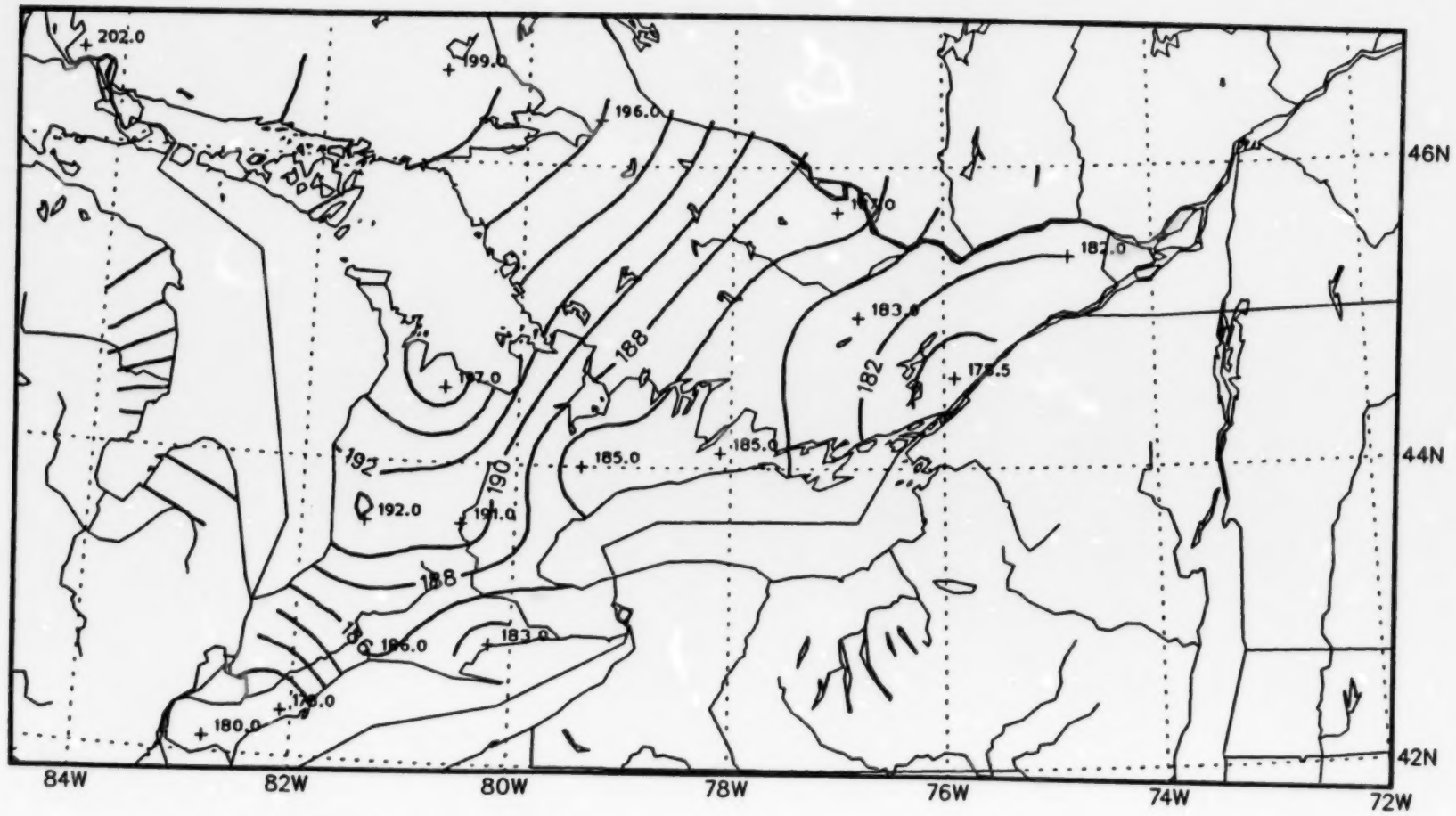

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FIGURE 8

CHANGE (IN DAYS) IN HARVEST DATE FROM GFDL SIMULATION

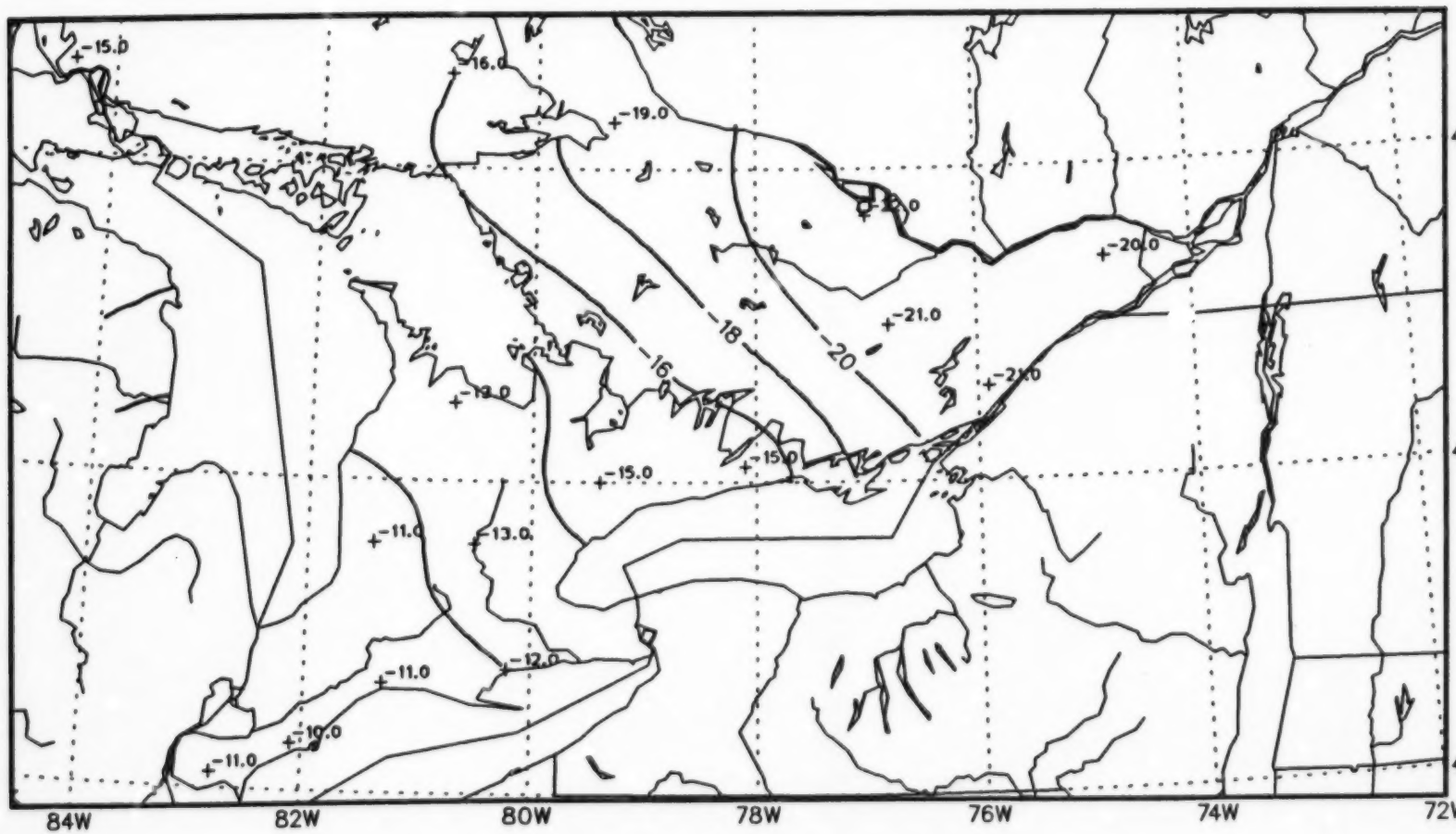

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FIGURE 9

CHANGE IN YIELD (%) AFTER CO2 DOUBLING USING GFDL

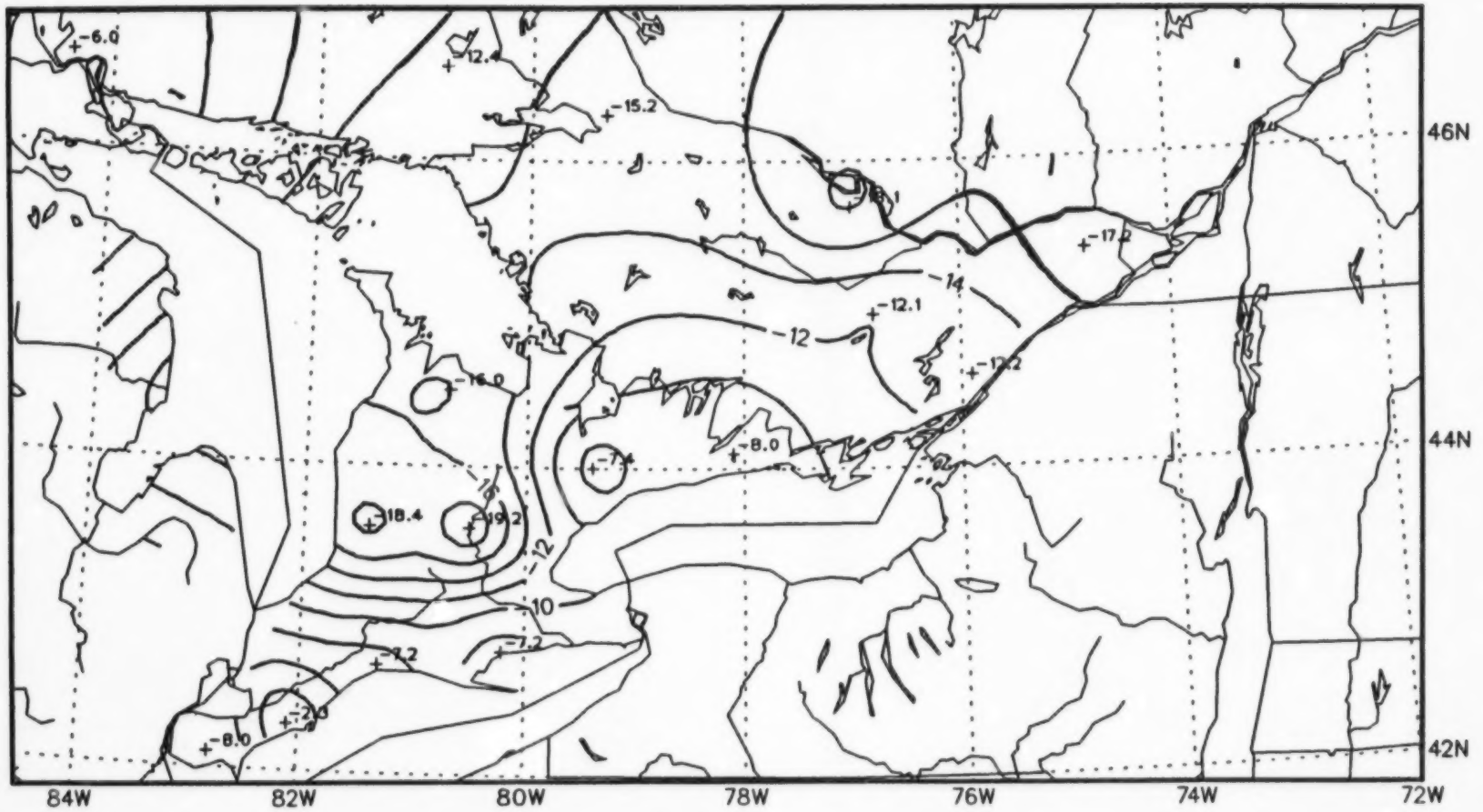

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FIGURE 10